A PORTABLE SELF-CONTAINED SYSTEM FOR THE CONTINUOUS ELECTRONIC RECORDING OF MOISTURE CONDITIONS ON THE SURFACES OF LIVING PLANTS

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PREFACE

This report describes an electronic recording system for quantitatively monitoring the moisture conditions on the surfaces of the aerial parts of living plants. Details of construction, cost, and performance are given.

The author expresses appreciation to L. F. Miller for assistance in building the prototype instrument and thanks James J. Cook for his contributions in the development and construction of the wetness recorder. Both individuals, now retired, were former employees of the Facilities and Engineering Directorate, U.S. Army, Fort Detrick, Frederick, Md.

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SUMMARY

Changes in electrical resistance on plant surfaces caused by changes in surface moisture conditions are detected by microclip metal electrodes, a pair of which comprises a single sensor. The instrument records on one chart the input from two sensors or from two groups of sensors when the sensors within each group are wired in parallel. The unit is portable, suited for field use, and will operate for 2 weeks on each fresh set of dry-cell lantern-type batteries, either two 6 V in series or one 12 V. The small alternating current of 8 μA that flows in the sensing circuit prevents polarization and heating effects and, along with the small size and mass of the sensors, reduces disturbance of the microclimate on the plant surface. The circuit described is suited for use as an input for data acquisition and computer purposes.

The spacing between electrodes of the sensing microclips, temperature, radiation, and windspeed did not affect the recorder's performance. However, the pressure of the microclip sensors on the plant tissue, the type of plant tissue, and wide, sudden fluctuations in the relative humidity did affect the input signal.

INTRODUCTION

The frequency and length of periods during which the aerial parts of the green plant, such as leaves, stems, and floral parts, are wet by a film of moisture are primary factors in the initiation and spread of diseases caused by foliar pathogens. The germination, formation, liberation, dispersal, and deposition of propagules and the rate of lesion enlargement in many important diseases may all be affected by moisture conditions. Rain is recorded routinely in many field investigations, but dew deposits and guttation have not been measured as a regular practice.

Estimates of dew occurrences and duration on foliage have been made using artificial surfaces for the collection and recording of condensed water. These devices have provided useful information, but all have recognized limitations in precisely defining moisture conditions on various types of plant surfaces (*4*, *7*).[2] Using the film of moisture on the plant surface directly to control a recording system offers increased precision and automatically compensates for differences in surface characteristics and growth habits among various types of vegetation.

An automatic moisture recorder was built by Winters and Small (*8*). This unit had a single probe attached to a very thin insulating disk of glass or rubber, which was held flat on the leaf surface. When a film of water bridged the insulator, electrical contact was established between the probe and the leaf, and the plant body served as the conductor to the soil,

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[2]Italic numbers in parentheses refer to Literature Cited, p. 12.

which was the common ground. By appropriate circuitry, the presence or absence of the film of moisture resulted in a voltage change in the grid of a vacuum tube. This change was amplified and transduced to activate the pen of a 7-day clock recorder. As designed, this instrument required a source of 110 V a.c. power.

An electronic moisture recorder was developed (*2*). It utilized two probes about 1 cm apart that clamped on the leaf. The probes were glass cover slips, 0.2 mm thick and 1 by 1 cm square, which were coated on the upper surface with rhodium metal. When moisture connected the leaf surface with the upper surface of the glass probes, the voltage change was used to control a circuit, which actuated a relay connected to the pen of a 7-day clock recorder. This system did not use the plant body as a conductor to the soil to complete the circuit, but it did require a source of 110 V a.c. power.

A transistorized unit for recording wetness on ryegrass leaves was developed in New Zealand (*9*). The sensors were microclips made of 26-gage hard-drawn brass wire. They were used in pairs with a 1-cm spacing between each clip of the pair. Usually eight of these pairs wired in parallel were employed at any one measuring location to give a single continuous record of leaf wetness. An alternating current of 3 Hz was used in the measuring circuit across the leaf elements. Variations in leaf wetness changed the voltage values between the collector of a transitor and a variable resistor. This voltage served as the input to a potentiometric strip chart recorder with a range of 0.5 mV. The measuring and recording instruments were housed in a building and were electrically connected to the field sensor junction box by a polyvinyl chloride-covered twin conductor cable. The authors did not state whether the recorder required a line power source.

An electronic leaf wetness recorder was described from the Netherlands (*5*). This device required a line power source and a relatively expensive potentiometric recorder. The deflection as the leaf surface changed from dry to wet because of rain was only about one-tenth of full scale on the published chart curves.

This report describes the design, construction, and performance of an electronic instrument for continuous recording of the moisture conditions on the living plant surface. The portable, battery-operated unit accepts inputs from two sensing locations and can be used on any type of vegetation, such as pasture grass, corn, and forest trees. This instrument was developed from a prototype unit that was demonstrated at the national meeting of the American Phytopathological Society in Spokane, Wash., in August 1969.

CONSTRUCTION OF RECORDER

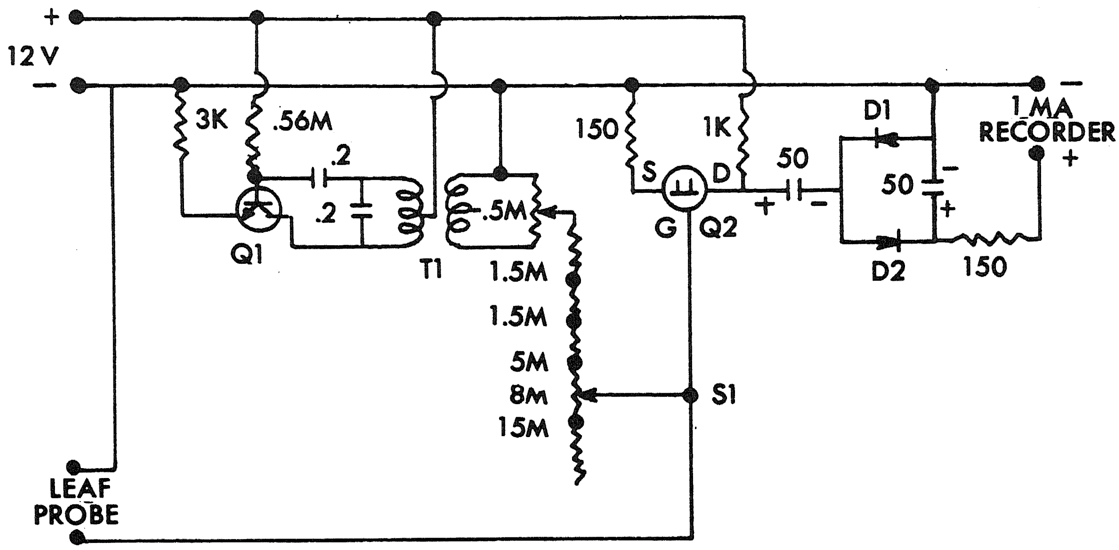
The transitor Q1, transformer T1, and associated capacitors and resistors (fig. 1) constitute an oscillator, which produces an a.c. sine wave of about 20 V at a frequency of about 59 Hz. Transformer T1 is connected with its 10,000-ohm winding driven by transitor Q2 and with its 5,000-ohm winding feeding the 0.5-megohm "Trimpot." The frequency and voltage magnitude can be varied slightly by substituting other values of resistance, or capacitance, or both. This voltage is suitably attenuated by the 0.5-megohm Trimpot and applied through the range resistors, where a switch provides values of 1.5, 3, 8, 16, or 31 megohms, to one electrode of the leaf probe and to the gate of transitor Q2. This is a general-purpose field-effect transitor with three terminals: Source (*S*), gate (*G*), and drain (*D*). Conduction is from source to drain but is governed by the voltage relationship of the gate to the source. The other leaf electrode (negative) is connected to the common ground.

The output of Q2 is passed through a voltage doubler network consisting of diodes D1 and D2 and associated capacitors. This circuit also eliminates pulses of the alternating current. A resistor connected in series with the 0- to 1-mA galvanometer in the recorder is selected at the proper value to obtain full-scale deflection with an open circuit between the leaf probes.

The circuit described here provides the necessary sensing and amplification for a single input to a galvanometer. Although the oscillator could be used to power more than one amplifier, some interaction between channels occurred when this was done; therefore a separate circuit was used for each leaf-sensing input. This input could come from a single sensing probe or from probes in different areas wired in parallel.

Sufficient output power is available from this circuit to drive directly the galvanometer used in most commercially available recorders. A Rustrak time-sharing recorder providing two channels was used in this study. It has a d.c. driven chart motor and a 0- to 1-mA galvanometer range.

Polarization, which could injure plant tissue and



Parts List[1]

Recorder - RUSTRAK Model 288, with 12-v d-c chart drive and 1 ma galvanometer: single channel, $135.; dual channel, $178.

T1 - Transformer, Allied Radio Type GT14PC, 1 at $5.37

Q1 - Transistor, Type 2N697, 1 at $0.65

Q2 - Transistor, Type HEP-802, 1 at $2.60

D1, D2 - Diode, Type IN926, 2 at $0.25 ea

S1 - Switch, 5-position, 2-pole, "Centrallab" Type 2003, 1 at $3.25

Capacitors: .2-mfd., 15-v, 2 at $0.50 ea
50-mfd., 15-v, 2 at $0.55 ea

Resistors (all ca. $0.10 ea):

150-ohm, .25-watt, 2 ea
1,000-ohm, .25-watt, 1
3,000-ohm, .25-watt, 1
.56-megohm, .25-watt, 1
1.5-megohm, .25-watt, 2
5-megohm, .25-watt, 1
8-megohm, .25-watt, 1
15-megohm, .25-watt, 1

Potentiometer, .5-megohm, "Trimpot" Type 3006, 1 at $2.00

[1] Double above quantities (except for recorder and switch) for 2-channel operation.

Figure 1.—Circuit diagram, parts list, and approximate 1973 prices for components of electronic wetness meter.

affect the input signal during extended periods of wetness, is prevented by using an alternating current in the sensing circuit. The value of the current is small, less than 8 μA, even when the surface is saturated, and it causes negligible heating of the water film. For these reasons and because the microclip electrodes are small in size and mass, the microclimate on the plant surface is not disturbed by the sensing system.

The plant-sensing electrodes are microclips made of hard-drawn stainless-steel wire of a gage and size appropriate for the test plant species (fig. 2). The microclips are electrically connected by short lengths of FORMVAR magnet wire of 24, 28, or 30 gage to 300-ohm television twin-lead wire, which is wired into the instrument. The TV wire is used to minimize capacitive reactance between the two sensing electrode leads. The shorter magnet wire leads attached to the microclips provide low mass and flexibility and allow the sensors to be attached to leaves without weighting down the leaf or restricting its natural movement.

A single 12-V d.c. supply (usually two 6-V dry-cell lantern-type batteries, series connected) provides power for the electronic circuit and for the Rustrak recorder with its chart drive motor and time-sharing relay. Two weeks of continuous service may be expected from a fresh set of batteries. We have successfully recharged these batteries with an automotive-type trickle charging unit. For best recharging results, batteries should not be used when their voltage under load drops below 10 V, and they should be promptly recharged at a rate not in excess of 0.4 A. A resistor (typically 5 ohms, 5 to 10 W) inserted in either lead between the battery charger and the batteries will insure a safe charging rate.

A Plexiglas cabinet was made in such a way that the recorder and the amplifier could be inserted into it as separate modules. The power and plant-sensing leads plug into the case, and external switches activate the circuits. This system is adequately rugged and suitable for laboratory and greenhouse use. For field operation the Plexiglas case and the power pack are slipped into weather-tight wooden cases (fig. 3).

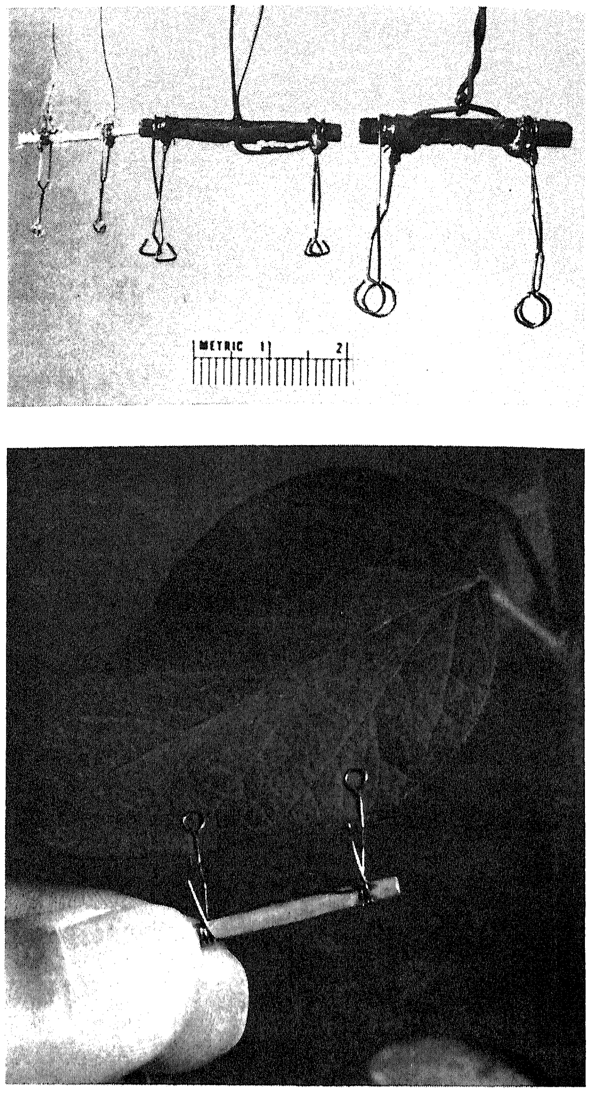


Figure 2.—*Above*, microclip sensor attached to soybean leaflet. *Below*, various sizes of microclip sensors; smallest is suitable for fine grass or for flower petals.

CALIBRATION AND OPERATION OF RECORDER

Make all connections between the power supply, recorder, and sensing leads, but do not attach leaf probes to plant tissue. With the range resistor switch set at some intermediate value, usually 3 or 8 megohms, and an open circuit between the leaf probe electrodes, adjust the 0.5-megohm Trimpot potentiometer to give a full-scale deflection on the galvanometer.

Attach the probe electrodes to the plant surface to be monitored. The galvanometer will deflect usually to between 80 and 90 percent of full scale when no moisture is present on the surface in the area of the electrodes. This is because the high resistance between the leaf electrodes permits only a slight current flow to "bleed" to ground and the voltage at the gate of Q2 is near its peak value, permitting

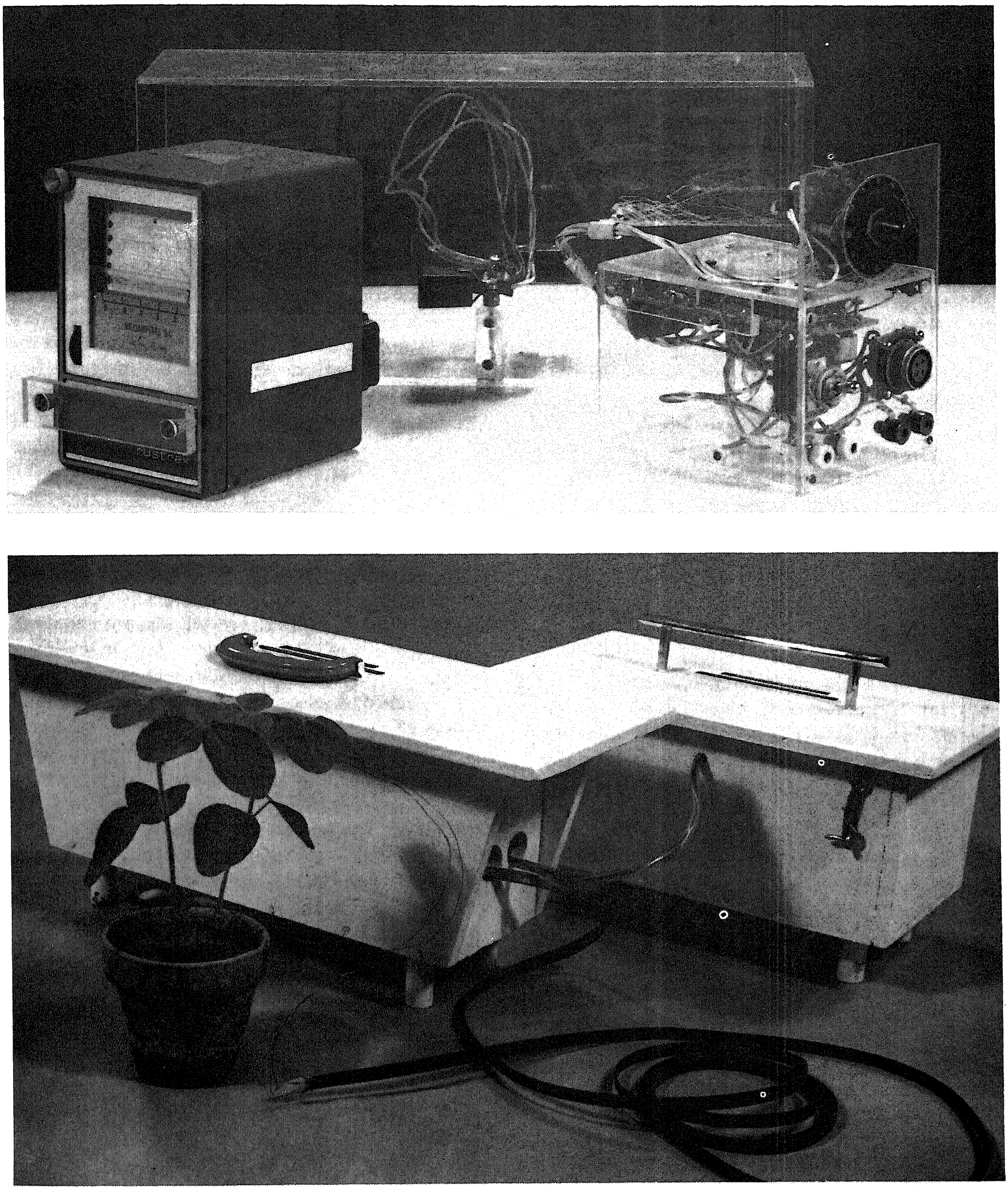


Figure 3.—*Above*, electronic wetness recorder showing amplifier module (*right*), recorder (*left*), and Plexiglas case (*background*). Recorder and amplifier plug into case to make a compact laboratory instrument. *Below*, wetness recorder packaged for field use; battery power supply (*right*) and recorder-amplifier unit (*left*) in weather-tight cases.

conauction from the source to the drain to drive the galvanometer arm near full-scale deflection. As moisture forms on the plant surface, the resistance between the probe electrodes decreases, more current flows to ground, and the voltage decreases at the gate of Q2, resulting in a lower current supply to the galvanometer and a down-scale deflection. At saturation the resistance becomes very low between the probe electrodes, and the recorder reads <5 percent of full scale.

The actual resistance settings selected will be governed by the electrical characteristics of the foliage and the degree of sensitivity desired. The lower the resistance, the greater will be the amount of water on the plant surface required for a given down-scale deflection. A fine-misting atomizer can be used to approximate various intensities of dew and to select rapidly the best resistance settings for the desired response.

RESULTS AND DISCUSSION

The recorder has been tested in laboratory dew chambers and in the field for various periods from 1970 to 1974. It has recorded wetness satisfactorily on leaves of corn, wheat, soybeans, ash, maple, numerous turf grasses, and common weeds. Wetness on petioles, stems, and floral parts has also been recorded. Some factors affecting the operation of the instrument are discussed here in detail.

Effect of range resistance settings on recorder readout.—Selection from 1.5-, 3-, or 8-megohm resistance values generally provided a satisfactory recorder readout with the plant species tested. At each of these values a series of readouts was obtained using a range of known fixed resistances across the sensing probe electrodes (fig. 4). A low meter reading corresponded to a low resistance between the probe electrodes. The 3-percent readings are similar to those observed when probes were on saturated plant surfaces. The meter readings were reproducible within less than one scale unit for each resistance tested across the probe electrodes.

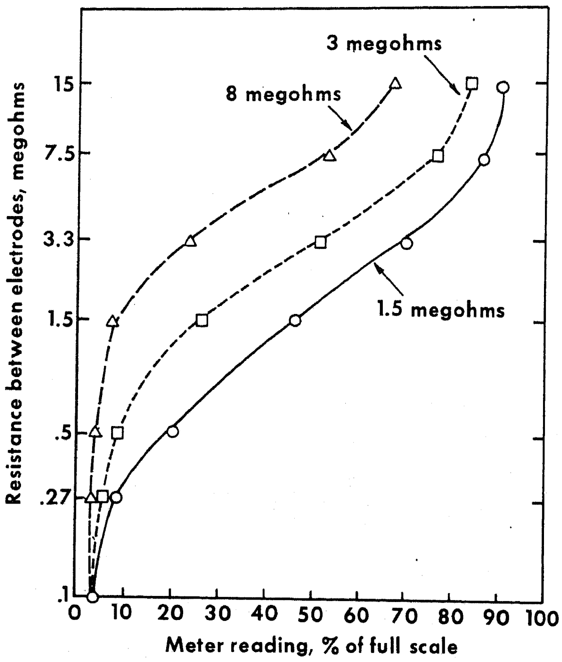


Figure 4.—Meter readings obtained on wetness recorder at 1.5-, 3-, and 8-megohm settings of range resistors using known fixed resistances across electrodes of sensing microclip. Galvanometer range was 0-1 mA full scale. Meter reading for open circuit with air gap between electrodes was 95 percent and for short circuit with copper wire connecting electrodes was 0 percent. Data points were plotted on semilog 4-cycle paper.

Effect of microclip characteristics.—The distance between the two electrodes of the sensing microclips was not critical. Spacings from 0.5 to 3 cm were tested, and the input to the meter was not changed.

Microclips made from stainless-steel or Nichrome wire did not obviously corrode or cause leaf injury when attached to foliage for up to 14 days in the field. A material now being tested that shows promise is a silver-coated wire of pretempered beryllium copper.

The effect of the pressure of the microclip on the conductive properties of a dry soybean leaf was determined. The microclips used were made of hard-drawn, stainless-steel, 0.5-mm-diameter wire, formed into contacting surfaces as smooth, flat loops of 3-mm diameter. The following data were obtained with range resistors set at 3 megohms:

Pressure of microclips against leaf surface (g per mm²)	*Meter reading (percent of full scale)*
2.7	80
3.2	80
3.7	80
4.7	74
7.7	53
12.7	48
22.7	43
92.7	25

The pressure on the plant surface by the microclips markedly affected the current flow between

electrodes. A pressure from about 2.7 to 3.7 g per square millimeter did not change the meter reading, but as pressures exceeded 4.7 g, the meter read progressively farther down scale with increasing pressure. Some leaf injury occurred at 22.7 g and it was severe at 92.7. An initial meter reading of 25 at this last pressure dropped rapidly to zero as the microclips cut into the leaf.

These results emphasize the need to standardize the clip pressure to suit the foliage to be monitored. The obvious advantage of strong-clamping microclips is their tenacious grasp on the plant surface, which in the field makes them difficult to dislodge by violent wind whipping. This desirable characteristic must, however, be balanced against the need to prevent down-scale deflections caused by excessive pressure and gouging, which might be mistakenly attributed to external surface moisture.

Effect of plant differences.—All plants used were grown in clay pots in the greenhouse and were brought into the laboratory for the test period. One sensing probe with a contact pressure of 2.5 ± 0.5 g per square millimeter was used for all readings. The range resistor setting was 3 megohms. After initial attachment of the microclips to the plant surface, there was often a short period of usually less than 6 minutes of meter "drift," after which the reading stabilized. The meter open circuit reading was 97. Each meter reading given is from a separate area of attachment of the probe electrodes on the indicated plant surface. The following wetness meter readings were recorded from the dry surfaces of several plant species:

Plant, type of tissue, and condition	*Meter reading (percent of full scale)*
Soybean, mature terminal leaflet of 2d trifoliate:	
Under moisture stress	94, 94, 93
Not under moisture stress	90, 90, 93
Geranium:	
Mature leaf, plant 1	94, 91, 91
Youngest leaf, plant 1	81, 82, 84
Youngest leaf, plant 2	83, 86, 87
Flower petal	81, 80, 82
Cowpea:	
Mature leaf	78, 75, 70
Young leaf	30, 32, 30
Stem section	90, 89, 89
Rice:	
Primary leaf	67, 60, 60
1st secondary leaf	54, 58, 59
Sheath at base	56, 52, 50
Corn:	
1st leaf, dead, dried	96, 96, 96
4th leaf, green	92, 92, 94
6th leaf, green	94, 91, 93
7th leaf, at tip	82, 80, 83

These data indicate that differences between species in their dry surface conductivity can be substantial, as shown with soybean or corn leaves when compared with the young leaf of cowpea. Although of less magnitude, the difference between the rice and most of the other plants tested was great enough to recommend a lower setting of the range resistors if monitoring of rice foliage wetness was desired. The difference between leaves of different ages on the same plant was largest with cowpea. In such an extreme instance, the range resistors could be set down to 1.5 megohms, driving both the mature and young leaf readings up scale. Additional adjustments of the Trimpots could be made until the dry readings for each leaf were reasonably the same and far enough up scale so as to provide good response to surface wetness.

These observations are presented to show the range of values that may occur in studies of leaf wetness and to stress the necessity of establishing for each sensing situation a dry plant baseline so that surface moisture may be more quantitatively measured.

Differences in internal moisture did not result in significantly different meter readings for the two soybean leaves. One was visibly wilted and drying from withheld watering and the other was upright, turgid, and well watered.

Effect of different intensities of surface water.—The sensitivity of the wetness meter to surface water in the area of the sensing microclip is determined by the range resistance and the Trimpot settings, as discussed previously. A study was done with the Trimpot adjusted to give a 99 percent of full-scale reading with an open circuit and the range resistors set at 3 megohms. The microclip probe was attached to a freshly excised soybean leaflet of known area, and the leaflet was placed on a nonconducting surface on an analytical balance. The dry reading was 78 percent of full scale. A very fine mist of distilled water from a calibrated nebulizer was deposited evenly on the leaflet. Different densities of water were deposited, and the increase in mass and the corresponding meter deflection were recorded.

The data in figure 5 demonstrate the characteristics of the instrument in recording different intensities of surface water in a quantitative manner.

From a dry leaf condition, the deposition of about 0.4 μg of water per square millimeter caused a down-scale deflection of the meter of 8 percent. This amount of water was not macroscopically visible. As the leaf surface became wetter, increasingly more water was required for a unit down-scale deflection. As shown in figure 5, about 200 μg of water (H_2O) per square millimeter of leaf area produced a totally saturated condition with a zero meter reading. This amount of visible water as dew would be subjectively described as heavy or copious.

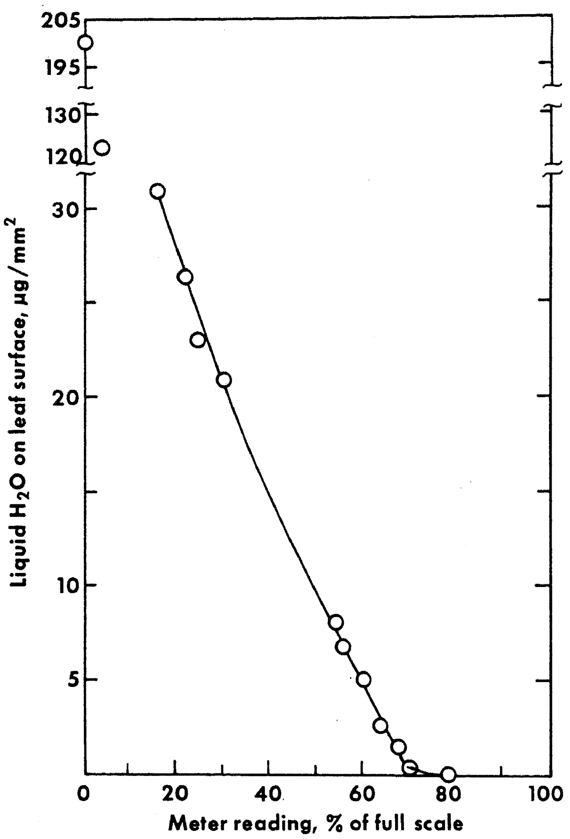


Figure 5.—Readings on wetness meter with various intensities of water (H_2O) on mature soybean leaflet. Range resistor setting was 3 megohms and microclip pressure was 2.5 ± 0.5 g per mm². Open circuit meter reading was 99 percent of full scale.

Effect of relative humidity.—Very rapid changes in the relative humidity (RH) caused deflections of the meter needle. When a dry soybean leaf, with a reading of 85 percent of full scale in air at about 25°C and 29 percent RH, was suddenly subjected to air at the same temperature but at 95 percent RH, the needle steadily deflected down scale, reaching 40 percent of full scale within 8 minutes. After this initial deflection, the needle slowly returned to its original dry reading and read 78 percent after 1½ hours. The range resistor setting was 3 megohms in this test. At 1.5 megohms the deflection was less than 10 percent of full scale when the test was repeated. The effect of RH is still being studied. It is difficult to determine whether sudden, wide increases in RH result in some condensation of water on the plant surface, a layer too fine to be detected by available methods.

In the field an erratic tracing of the dry leaf condition sometimes has been observed. This may be caused by sudden changes of RH near the leaf surface, such as would occur with intermittent sun and shade conditions. Usually this tracing is high up scale and is interpreted to signify a dry surface condition. When dew forms, the down-scale trace is obvious and fairly smooth.

Effect of leaf temperature and incident radiation.—Instrumented leaves of potted plants of soybean and corn were moved suddenly from one temperature to another in the dark. Very slight deflections of the meter needle were observed, even when the temperature change was rapid and large, as from 29° to 3°C.

Leaves receiving very low levels of light were suddenly illuminated by a tungsten filament floodlamp. Light readings at the leaf area for blue, far red, and red were 6, 65, and 40 μW per square centimeter per nanometer as measured by a plant growth photometer (Model IL150, International Light, Inc., Newburyport, Mass.). Their surface temperature rose from 26° to 35°C within minutes, during which the meter reading went from 85 to 89 percent of full scale, then dropped back to about 85, and remained fairly steady. When the light was switched off after 10 minutes of operation, there was less than 2 percent of meter deflection during the next 5 minutes. The differences noted in this and other tests were negligible and could be caused by changes in the relative humidity at the plant surface.

Effect of windspeed.—Controlled, artificially generated winds of near zero up to about 15 m per second did not affect the readings for dry corn and soybean leaves, even when the leaves were whipped violently. The microclips must be unrestricted in their motion, because a "snubbing" tendency could cause the clips to cut into the leaf surface and result in a response similar to that caused by a too heavy clip pressure. Also, strong, gusty winds cause the leaves to rub against each other and result in minor, temporary fluctuations in the recorded meter values.

Performance of wetness recorder in controlled dew chamber.—In a dew chamber (*1*) at 26.5° ± 0.5°C, deposition of dew on leaves of potted soybean plants was recorded at range resistor settings of 1.5, 3, and 8

megohms. After attachment of the microclips, the dry leaf readings were established. Then the plants were placed within the chamber in such a position that one instrumented leaf was parallel to and about 6 cm from the cold wall of the chamber and the other leaf was about 14 cm from the wall and partly shielded by surrounding foliage. After dew formation, the plants were put back in the laboratory air with sensors still in place. When the dry condition was again established, the range resistance setting was changed, and the procedure was repeated. The laboratory air was 24° ± 1.5° ± and 30 5 percent RH. The temperature of the walls of the dew chamber was nearly the same as that of the laboratory air, which was only about 2° below the dew chamber air temperature. Under these conditions the water would be expected to condense and form fairly slowly a very fine, light dew. The leaf nearer the cold wall would collect more dew than the leaf farther from the wall.

Because the microclips, foliage orientation, and laboratory and dew chamber conditions were kept constant, the rate of dew deposition on a given leaf was nearly identical at each range resistor setting. Differences in the recorded curves shown in figure 6 therefore demonstrate the effect of the range resistance values on the sensitivity and capacity of the wetness recorder.

At the 1.5-megohm setting (fig. 6, *A*), the dry readings were 84 and 93 percent of full. scale, respectively, for leaf 1 and 2. The initial down-scale

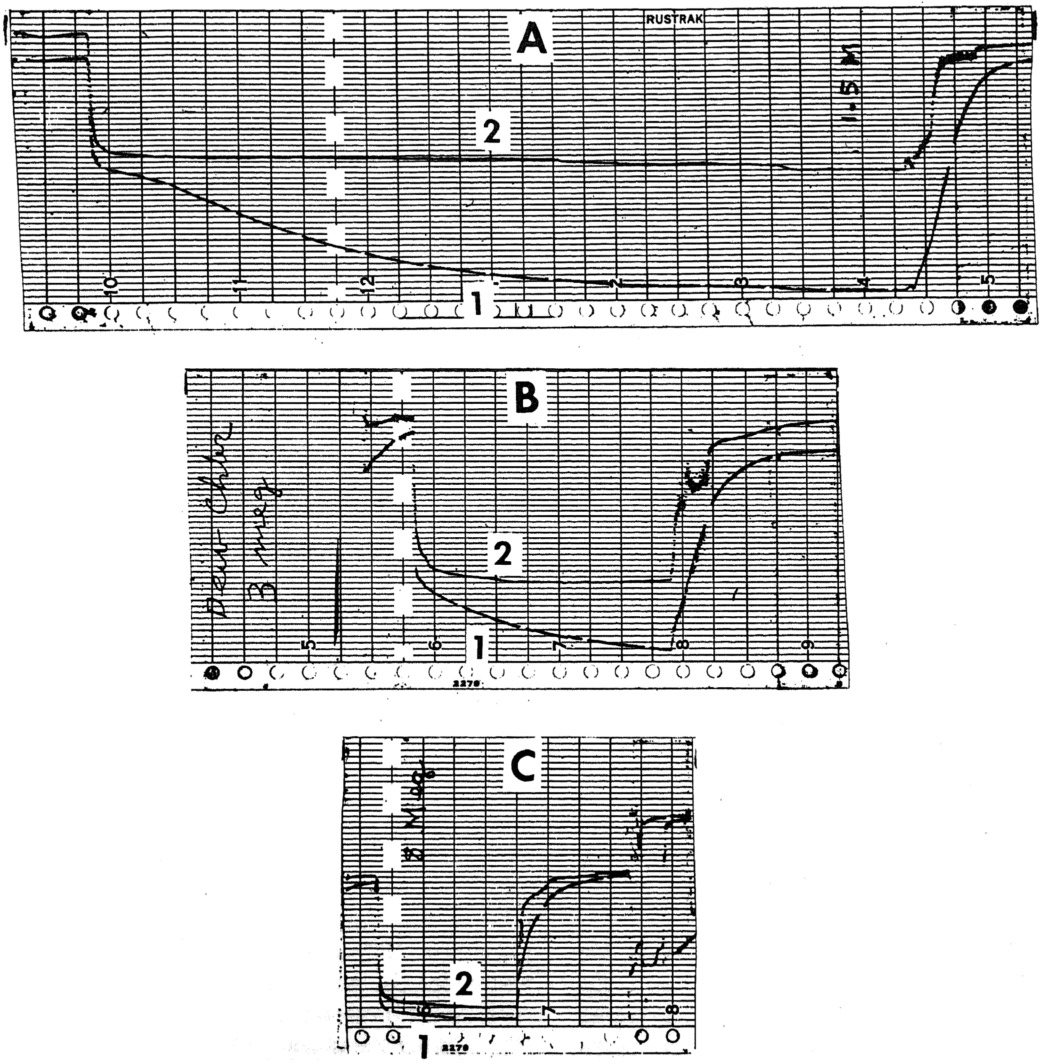


Figure 6.—Photographs of charts from wetness recorder during operation in laboratory dew chamber at 26.5° ± 0.5° C with range resistor settings of 1.5 (*A*), 3(*B*), and 8 (*C*) megohms. Sensors were on soybean leaves 1 and 2 that were 6 and 14 cm, respectively, from cold wall of chamber. The traces moved from left to right with time, and each vertical division on chart represents 1/2 hour.

plunge when the plants were suddenly placed in the dew chamber stopped at about 45 to 50 percent for both leaves. Dew increased slowly on the leaf nearer the cold wall (1) for at least 11 hours, as indicated by the continual down-scale recording. Very little further increase occurred on the leaf that was 14 cm from the cold wall (2). Both leaves began to dry at nearly the same time, but the wetter leaf (1) was not completely dry until 1 hour after the less wet leaf.

At the 3-megohm setting (fig. 6, *B*), the dry readings for both leaves were between 80 and 85 percent of full scale just before the plants were placed in the dew chamber. The initial down-scale plunge, denoting rapid condensation of water, stopped at about 25 to 35 percent for both leaves. The trace from the leaf 14 cm from the cold wall (2) stabilized about 2 hours after dew initiation at a reading of 25 percent. The leaf 6 cm from the cold wall (1) continued to accumulate dew, and its trace was still trending down scale when the plants were removed from the dew chamber.

At the 8-megohm setting (fig. 6, *C*), the dry leaf readings were 52 to 55 percent of full scale. Placing the plants in the dew chamber caused the typical down-scale plunge, which stopped at readings of about 6 and 9 percent for leaf 1 and 2, respectively. The traces for both leaves stabilized 2 hours after dew initiation, and additional dew would have no effect on the wetter leaf (1) recording and very little effect on that of the less wet leaf (2).

In each test a rapid down-scale deflection after placing the plants in the dew chamber was recorded. During the dry period the plants were at the laboratory air temperature, which was cooler than the air in the dew chamber. We believe a film of water, too slight to detect visually, condensed nearly instantaneously on the leaf surfaces when the plants were quickly placed in the warmer, high humidity chamber. Unlike the effect of rapid, large increases in RH discussed earlier, no up-scale recovery followed the initial down-scale plunge.

In these tests, borderline conditions for dew formation were provided. Examination with a hand lens was required to detect dew visually on the less wet leaf, even after 10 hours in the dew chamber. The wetter leaf did have visible dew, classified subjectively as very fine or light.

Field performance of wetness recorder.—The partial or complete short circuiting of the microclip leads and the dislodgement of probes or tearing of leaves in violent wind by the microclips were problems. The use of TV twin-lead wire, spatially separating the splices to the lighter magnet wire, and the thorough application of multiple coats of insulating varnish at splices and microclip connections eliminated accidental shorting. To prevent dislodgement of the clips and the tearing of the leaves, the mass of the microclips was reduced to the minimum feasible, the compressive force was adjusted to about 3 g per square millimeter, and the terminal end of the TV lead was anchored while allowing sufficient slack in the light magnet wire leads for natural movement of the plant.

Figure 7, *A*, shows the effect of light showers of rain lasting just a few minutes at "a" and "b." This contrasts sharply with the onset and buildup of dew recorded as a steady, gradual, down-scale trace beginning at "c." Dew on the grass leaf (1) shielded by the tree canopy above it formed more slowly than on the dandelion leaf (2) out in the open. Both leaves showed definite periods of wetness of about 10 hours. Drying began in the morning at the same time on both leaves and was completed in about 1 hour, as indicated by the abrupt up-scale swing and leveling off at the right of the chart.

Recordings were made from a grass leaf in the open and a leaf in the lower canopy of an ash tree, about 0.5 m inside the periphery. On a clear night with little wind, the grass leaf (1) showed a steady intensification of dew and within 2 hours after onset was thoroughly wet (fig. 7, *B*). The protected tree leaf (2) slowly acquired dew, reaching a maximum intensity about 4 hours after onset. The amount of dew was about one-third of that deposited on the grass leaf. The heavier dew deposit on the grass leaf increased the dew period as indicated by the drying curves. The tree leaf (2) began drying off at "a" and had returned to a dry condition at "b." The grass leaf (1) showed rapid drying at "c" but had not dried completely at "d," about 2 hours after the tree leaf was dry. Recordings from both leaves indicated a steady, dry condition before the onset of the second night of dew began at "e."

On a partly overcast night with intermittent winds and conditions not favorable for dew formation, both leaves showed a departure from the steady, dry, daytime condition (fig. 7, *C*). A Taylor-type dew meter (*3*) operating within 1 m of the instrumented grass leaf (1) indicated no trace of dew during this entire period. Nevertheless the steady, down-scale reading for the grass leaf (1) from "a" to "b" indicated that surface water was present, although less than 20 μg of dew per square millimeter.

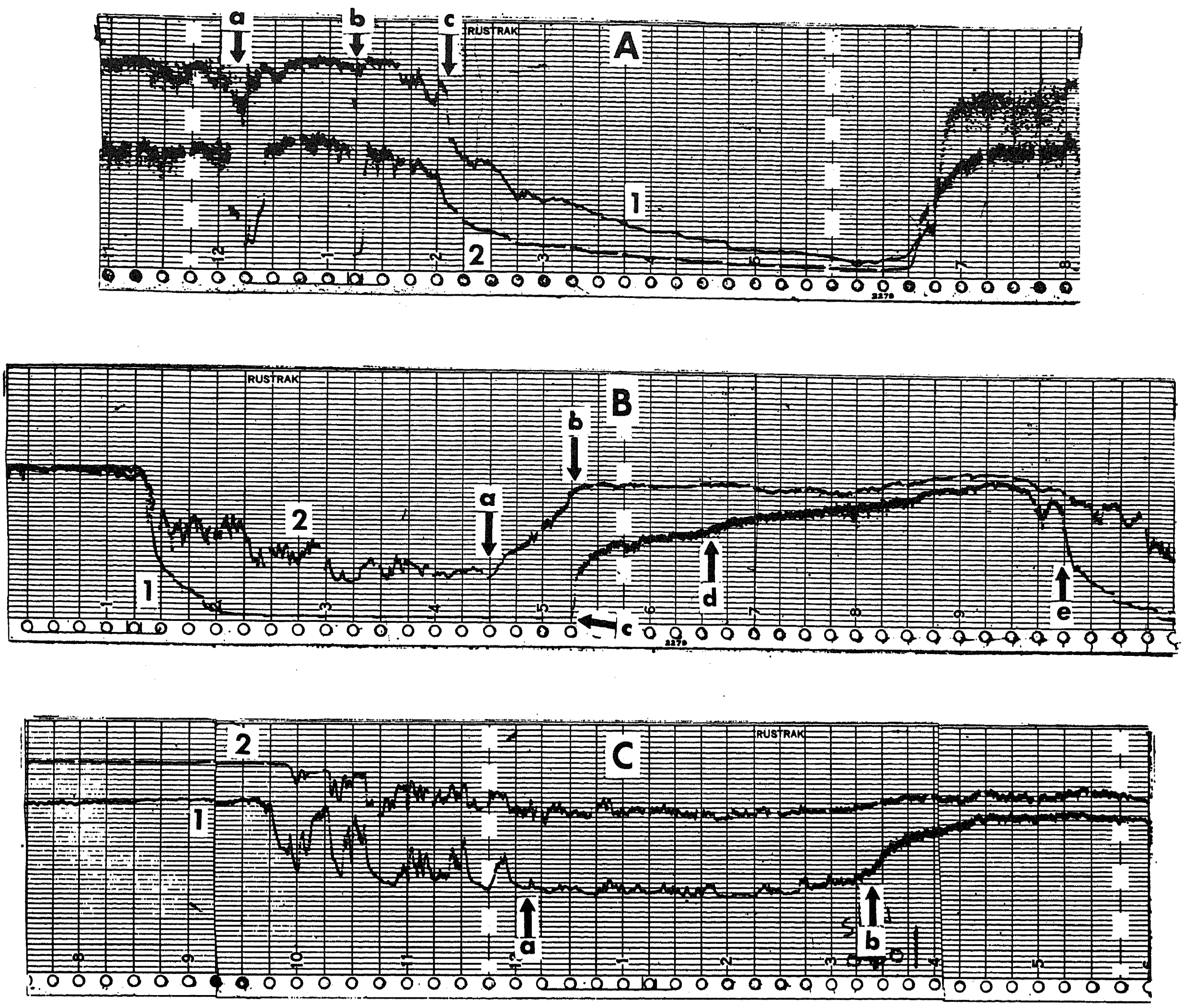


Figure 7.—Photographs of charts from wetness recorder during field operation with range resistance setting of 3 megohms: *A*, Recording from grass leaf (1) growing beneath ash tree canopy and from dandelion leaf (2) growing in low-cut grass 10 cm from grass leaf; *B* and *C*, recordings from grass leaf (1) growing in open and from ash leaf (2) in lower canopy of ash tree about 0.5 m within periphery of tree crown (*B*, clear night with little wind; *C*, partly overcast night with intermittent wind; *a-e*, scale readings discussed in text). The traces moved from left to right with time, and each vertical division on chart represents 1/2 hour.

GENERAL DISCUSSION

The quantitative determination of the RH at the plant surface and the condensation of water on the plant surface is difficult in a laboratory or dew chamber and particularly so in uncontrolled environments typical of field investigations. How important in epiphytology is the distinction between very high RH and the visually undetectable layer of water that must exist in conditions barely permitting dew formation? At what density does additional water in the film on the leaf become superfluous from the standpoint of the pathogen's requirement to initiate infection, colonize the suscept, or produce and release or interfere with the release of reproductive propagules? The practical value of quantitative answers to such questions is apparent from such work as Waggoner and Horsfall's (*6*), where spores of *Alternaria solani* after germinating in water were killed by arid air, but spores germinated at high

humidity were able to survive arid air conditions and continue to grow when returned to high humidity.

Wylie, Davies, and Caw (*10*) reported that the threshold for the visual detection of incipient condensation on a polished metal surface, using dewpoint hygrometric methods, is about 3 μg per square centimeter, and this deposit would contain about 5×10^8 droplets per square centimeter in a layer about 0.03 μ thick. The smallest amount deposited on the soybean leaflet in the study described here was about 40 μg per square centimeter. Although this amount was not visible under a 5X hand lens, it caused a deflection of the meter from 78 to 70 percent of full scale. Evidence permitting an evaluation of such low densities of water on disease initiation, development, and spread has not come to our attention. Probably a record of no dew during such periods has often been obtained in field studies. If so, this would place a different interpretation on the success of disease forecasting systems using periods of $\geqq$ 95 percent RH as a primary criterion, such as for potato late blight in certain geographical areas.

In general, airborne spores of pathogens causing foliar diseases are hygroscopic entities and as such would serve as excellent condensation nuclei, along with the myriad of other particles on the plant surface and irregularities in its surface. Because of such particles, irregularities, and hygroscopic areas, incipient condensation probably always forms on plants at surface temperatures above (possibly as much as 1°-2°C) the true dewpoint of the contacting air.

In controlled dew chamber tests along with field studies on infection and disease development, the use of the electronic wetness meter will shed some light on the problem areas discussed here. The following features of the instrument offer advantages in plant science research:

(1) The sensors can be used with any type of vegetation. If the sensing location is an exceptionally long distance from the recorder, as, for example, the top of a tall tree, the amplifier can be packaged separately and placed within 4 m of the sensing area. The leads to the recorder can be any necessary length.

(2) The moisture condition at the plant surface directly controls the input to the recording system.

(3) In addition to the frequency and duration of wetness periods, the intensity of the moisture is quantitatively recorded.

(4) The sensitivity of the response to moisture can be controlled to suit the research objectives, i.e., if incipient, very slight moisture films are being studied, a high range resistance setting can be selected.

(5) Discrete information on wetness can be obtained from very precise areas on plant surfaces. Alternatively, several sensors wired in parallel can be distributed over an extensive area to sample conditions from a wider population of plants.

(6) The instrument is independent of line power and can be used in any location. The chart driven at a speed of 0.5 inch per hour will run for 60 days. A fresh supply of lantern-type dry-cell batteries usually will operate the system for 2 weeks before the voltage drops below operational level. The time-sharing relay is the major consumer of power in the recorder described in this report. A single channel recorder could be used instead and result in a doubling of battery life.

(7) The system can provide an output, with or without the recorder operating, of 0-1 V d.c., or any convenient smaller range, for data acquisition and storage or direct computer input. Signals can be made compatible with those used for other parameters of interest in epiphytology, such as windspeed and direction, radiation, and temperature.

Although this report has dealt exclusively with the recording of moisture conditions on living plant surfaces, the system described could monitor surface wetness of nonliving materials, such as glass or plastic. It could also be readily applied as an alarm or control device, as in fungicide spray operations and mist propagation beds.

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